



ELSEVIER

Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Nuclear Instruments and Methods in Physics Research A 499 (2003) 415–427

**NUCLEAR
INSTRUMENTS
& METHODS
IN PHYSICS
RESEARCH**
Section Awww.elsevier.com/locate/nima

Commissioning results and applications

L. Ahrens, M. Bai, M. Blaskiewicz, M. Brennan, P. Cameron, R. Connolly, A. Drees, W. Fischer, R. Fliller, D. Gassner, J. Kewisch, S. Peggs, F. Pilat, V. Ptitsyn, T. Roser, T. Satogata, S. Tepikian, D. Trbojevic*, J. van Zeijts

Collider-Accelerator Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Abstract

This section describes both: successful commissioning of RHIC and the state of the art RHIC accelerator physics tools/applications. The commissioning provided collisions of the fully stripped gold ions at a beam energy of 65 GeV/nucleon in all four experiments “STAR”, “PHENIX”, “PHOBOS”, and “BRAHMS”. They collected more than $3 \mu\text{b}^{-1}$ of data. Measurements of betatron and dispersion functions have shown excellent agreement with predictions. Diagnostic results from tune-meter, wall current monitor, chromaticity, decoupling measurements, ionization beam profile monitor, Schottky monitors, etc. are shown. Progress towards stable gold ion beam stores with optimized luminosity is described [Proceedings of the HEACC2001 The 18th International Conference On High Energy Accelerators, March 26–30, 2001, Tsukuba, Japan, March, 2001]. Few major commissioning challenges are described first. The most important results, from some of the RHIC systems, are shown in the next section. In the following section bringing beams from two separate “blue” and “yellow” rings into collisions and measurements during long beam stores are described. In the summary part necessary steps and commissioning of additional systems during the next RHIC-2001 run are mentioned.

© 2002 Elsevier Science B.V. All rights reserved.

0. Parameters and performance goals for RUN-2000

Basic parameters of the previous RHIC RUN2000 are presented in [Table 1](#).

1. Commissioning challenges

Fully stripped gold ion beams Au^{79+} were injected into both blue and yellow rings from the AGS (Alternating Gradient Synchrotron) with

energy of 9.57 GeV (as presented in [Table 1 \[1\]](#)). The closed orbit of the beam was established with the orbit correction program (see [Fig. 1](#)). The program receives information from the beam position monitor (BPM) system, calculates corrections and communicates with the ramp manager. It sets the correction magnets to new values. Orbits in both rings were successfully corrected with a rms value of less than few millimeters as shown in [Fig. 1](#).

1.1. Chromaticity problem

The betatron tune measurements had shown unexpected sensitivity to momentum at the

*Corresponding author. Tel.: +1-631-344-3078; fax: +1-631-344-5954.

E-mail address: dejan@bnl.gov (D. Trbojevic).

beginning of commissioning. Due to high voltage problems of the injection kickers, the initial energy of gold ions was lowered a bit from the design one (currents in the dipoles were lowered from 545 down to 463 A).

The initial measured chromaticities (see Fig. 2) were quite different from the model predictions, due to a larger sextupole multipole component in

dipoles. A control of the power supplies and excitations of all magnets in RHIC is performed by sequencer, ramp, and the wave form generator manager (they provide a direct correspondence between the “model” of the accelerator and actual settings). Additional correction for 60 units of chromaticity was necessary to compensate for the larger values of the sextupole multipole within the

Table 1

Parameters and performance goals for RUN2000

Injection energy	$\gamma = 10.27$	$E = 9.57 \text{ GeV/n}$
Storage energy	$\gamma = 70.0$	$E = 65.1 \text{ GeV/n}$
Bunch intensity	0.5×10^9	
Number of bunches	56	
Transverse emittance	$15\pi \text{ mm mrad}$	Normalized 95%
Longitudinal emittance	0.3 eVs	Per nucleon per bunch
β^* @IP	$3m@2, 4, 8, 12 \text{ o'clock}$	$8m@6$ and 10 o'clock
Luminosity	$2 \times 10^{25} \text{ cm}^{-2}\text{s}^{-1}$	10% of design
Integrated luminosity	few μbarn^{-1}	

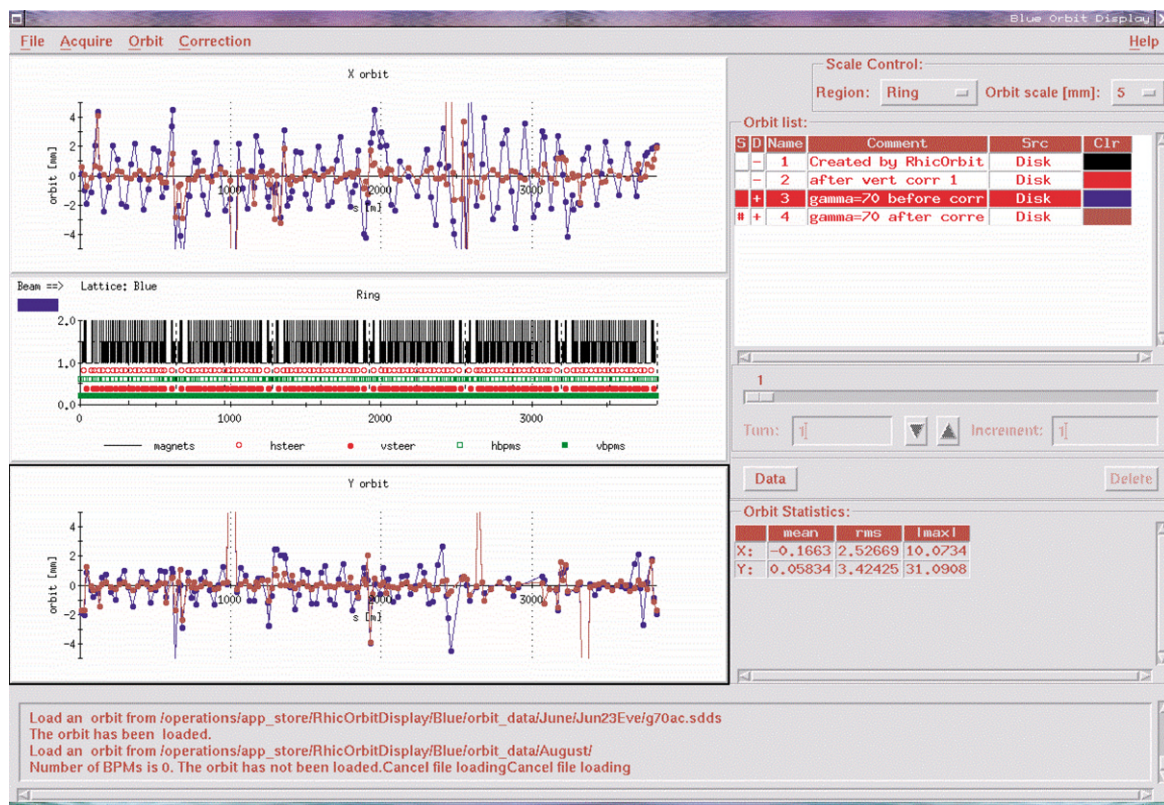


Fig. 1. Orbit correction in the blue ring. The blue color represents the orbit before correction, while the red is after the correction.

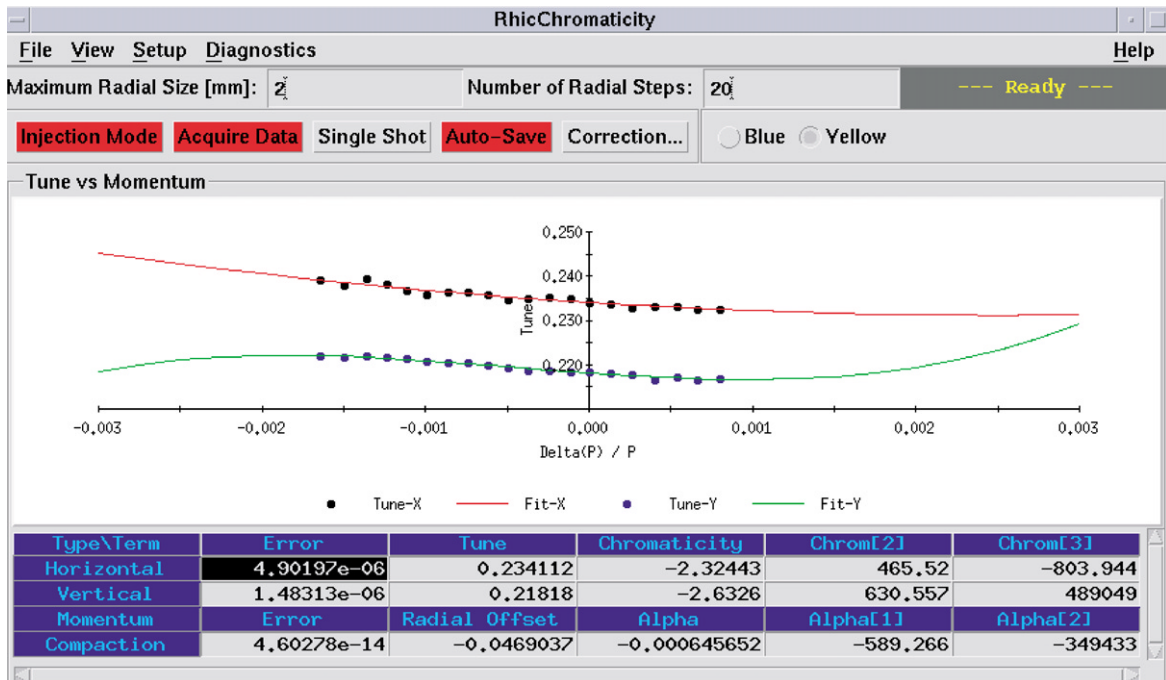


Fig. 2. Chromaticity measurements.

dipoles. A very easy to use chromaticity measurement application program automatically ramps for at least five RF radial offsets, triggers the tune measurement application program at each beam position and measures the chromaticity, as shown in Fig. 2. Very precise and reliable beam position monitors were available early on in the commissioning effort and allowed beam-based diagnostics to detect hardware problems. They also allowed a demonstration of excellent agreement between measured and accelerator models predictions. A discrepancy between the measured and expected betatron functions was the next challenge.

1.2. Finding a shunt power supply with a wrong polarity

With a help of on-line model a polarity of a specific shunt quadrupole power supply was changed with an opposite sign than expected. An agreement between the measured dispersion function and model expected dispersion with wrong polarity is illustrated in Fig. 3.

1.2.1. RF capture

Before any start of the ramp, the sequencer checked and set required values for different systems like RF, tune meter etc. Injected bunched were captured by digitally controlled synchronization between the AGS and RHIC RF systems. The whole RF system performed very reliably and the accelerating cavities were fully commissioned. Their high voltage status was connected to the permit link.

1.3. Measurements of the persistent current effect

Snap back and persistent current effects were additional concerns, which were measured and compared to predicted values [2]. The effect of the persistent currents was clearly visible at injection. The lifetime of bunches injected sequentially steadily improved with time over the first few minutes. The predicted and measured differences of the chromaticity, due to a time dependence of the sextupole multipole in dipoles, are in excellent agreement, as shown in Fig. 4.

Power supply Q89 with wrong polarity -Dispersion measurements

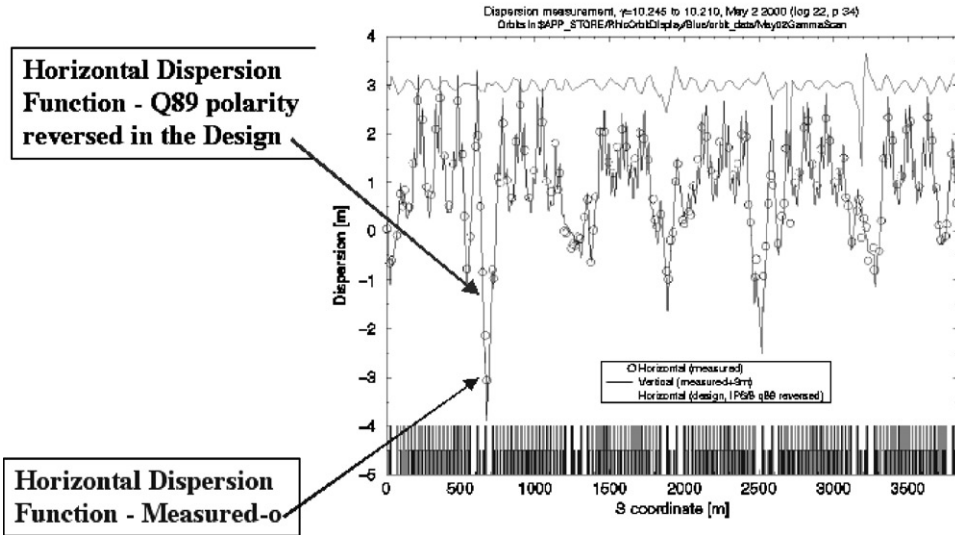


Fig. 3. Comparison between measured dispersion and the model where the Q89 power supply was reversed.

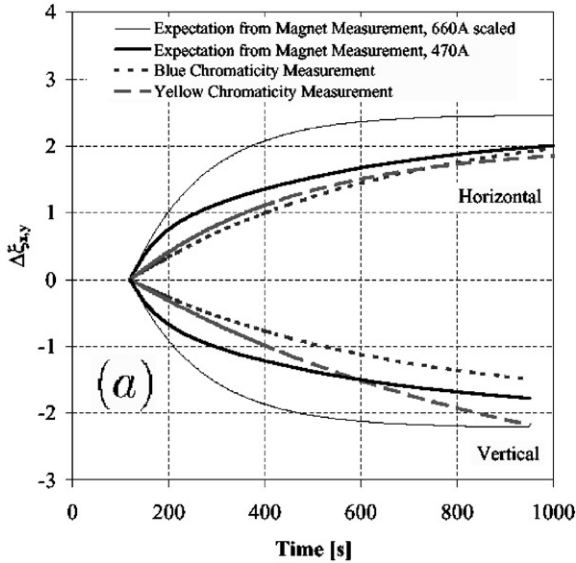


Fig. 4. Persistent currents: excellent agreement between the measured time dependence of chromaticities with predictions based on measurements of the sextupole component in the arc dipoles.

2. Acceleration

Unfortunately, RHIC is the first superconducting, slow ramping accelerator that crosses transi-

tion energy during acceleration. Although some beam loss and longitudinal emittance growth was observed from crossing transition energy, the effect was not excessive due to still lower beam intensity and a favorable lattice functions. The second order momentum dependence coefficient was measured [3] to be $\alpha_1 = -1.5$, and presented in Fig. 5. This was a favorable condition because it minimized momentum dependent (chromatic) effects at transition. Considerable number of the interaction regions (IR) quadrupole power supplies had not still being delivered (four of six) to RHIC at the time of the run-2000 period. This combination of two IR's tuned at $\beta^* \sim 8$ m and the rest of the IR's tuned at $\beta^* \sim 3$ m made betatron lattice functions favorable showing an agreement of the predicted and measured second order momentum coefficient $\alpha_1 = -1.5$.

2.1. Betatron tunes along the ramp

The acceleration cycle is shown in Fig. 6. At the picture two “blue” and “yellow” beam DC-Current Transformers (DCCT) signals are shown. Fifty-six bunches were filling first one ring. When the lifetime at injection was confirmed to be larger

than 30 min the other ring was filled with additional 56 bunches in opposite direction by a change of polarity of the switching magnet in the beam line from AGS to RHIC (ATR).

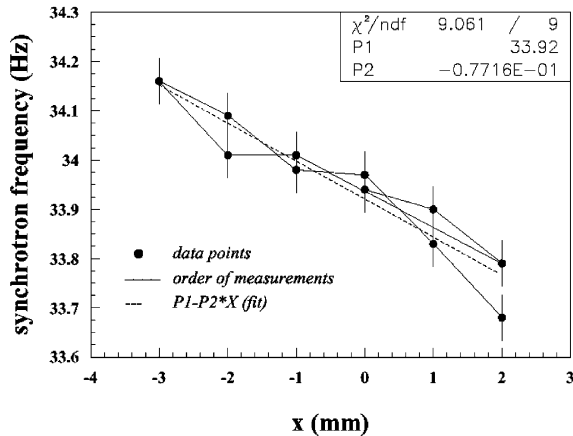


Fig. 5. Measured synchrotron frequency versus radial steering set point.

To accommodate easier transition crossing a first order γ_t jump was designed and built. Due to still missing power supplies for the γ_t quadrupole, during the RHIC RUN2000, the transition crossing had to be performed by the RF radial loop jump. To avoid the beam loss it was important to keep the partial tunes between the two resonances $1/10 = 0.2$ and $1/5 = 0.25$ during acceleration as shown in Fig. 7 by the tune measurements. A separate window of the tune meter system displayed the raw data, the FFT spectrum and the result for one measurement in one plane at the time. In order to track the tunes over a certain period of time, tunes were displayed as color-coded FFT spectra, shown in Fig. 7. The figure contains data from one ramp on August 6, 2000, including both planes in the Blue Ring. Raw data spectra as well as the derived tunes could be saved and archived. Other control parameters customize for various applications such as chromaticity measurements or others.

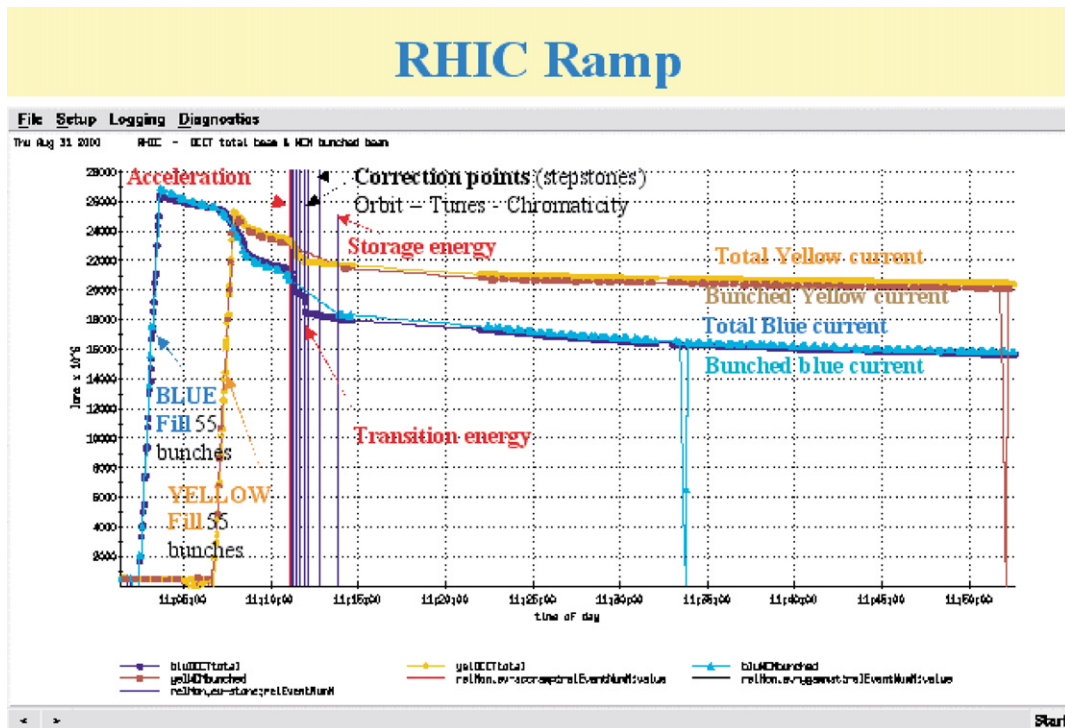


Fig. 6. Typical ramp during the RHIC RUN2000.

Tune measurements during acceleration ramp

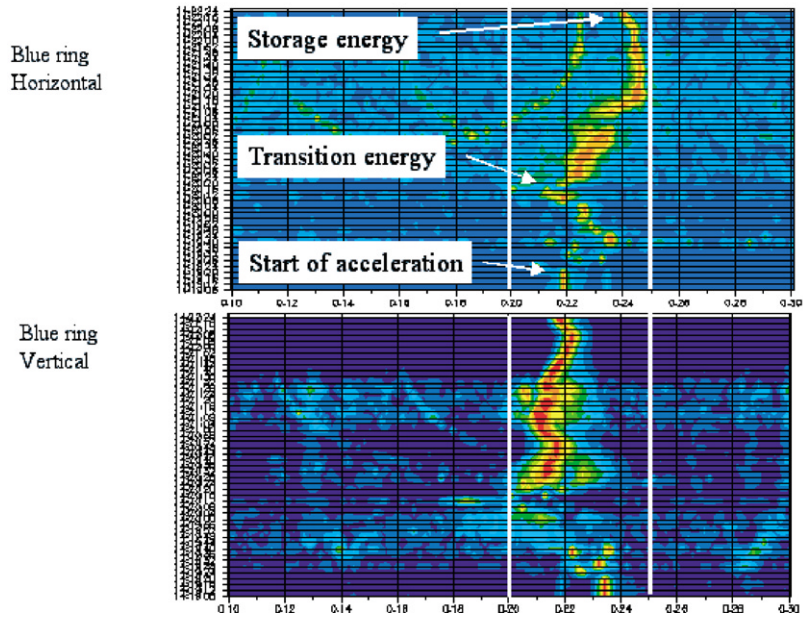


Fig. 7. Mountain range presentation of the betatron tunes along the RHIC acceleration. Tunes were monitored during a ramp on August 6, 2000, from injection up to flat top energy. Data is acquired every 4 s.

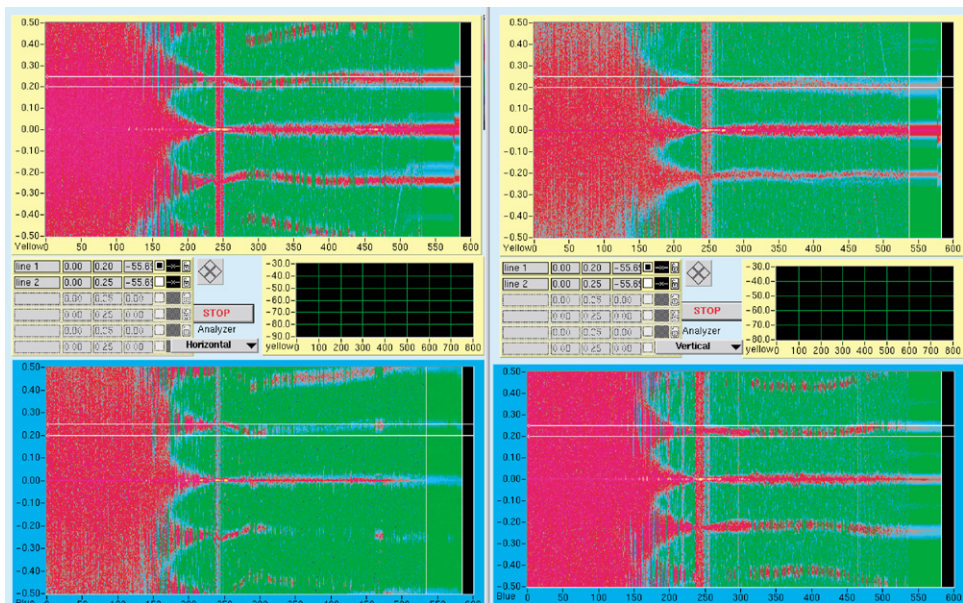


Fig. 8. Schottky signals of the betatron tunes along the RHIC acceleration.

Ionization Profile Monitor in the Blue ring

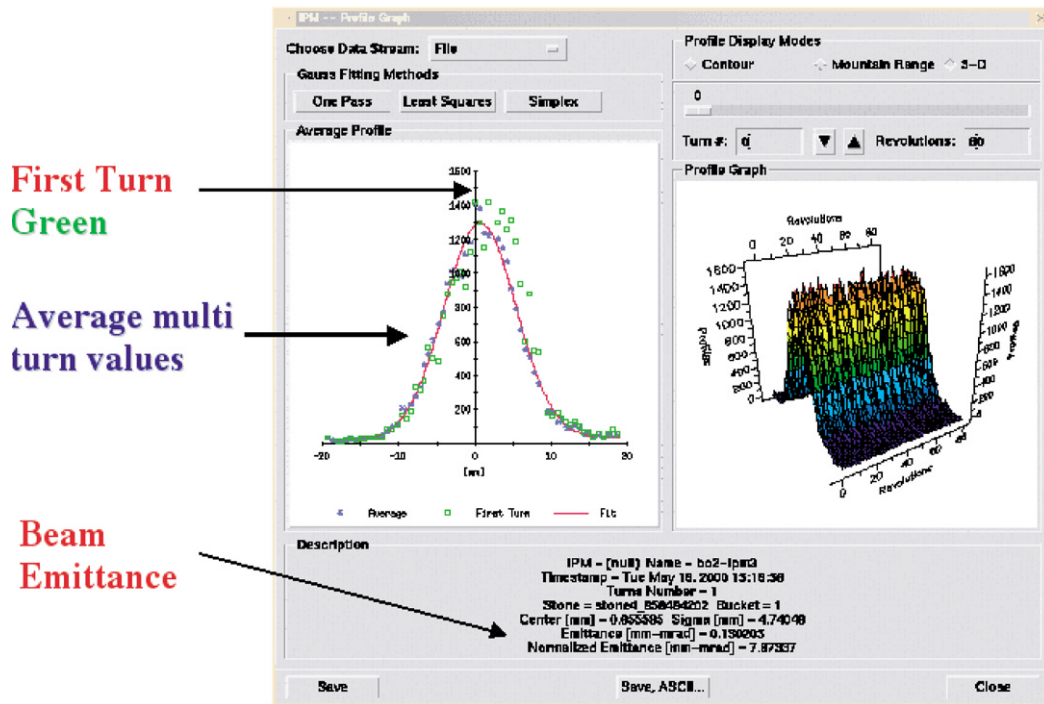


Fig. 9. Beam profile at injection.

Accelerating a gold bunch in RHIC

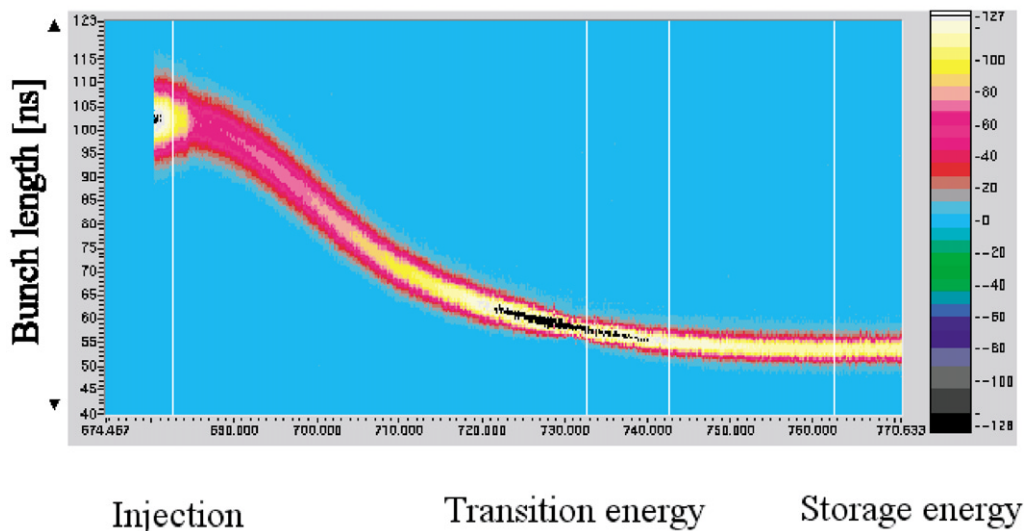


Fig. 10. Wall current monitor along the accelerating ramp in RHIC.

2.2. Schottky detector results

In addition to the excellent performance of the “tune meter” system with the “mountain range” display of the tunes along the ramp, the Schottky detector (built at the Lawrence Berkeley Laboratory) was successfully used. It provided accurately

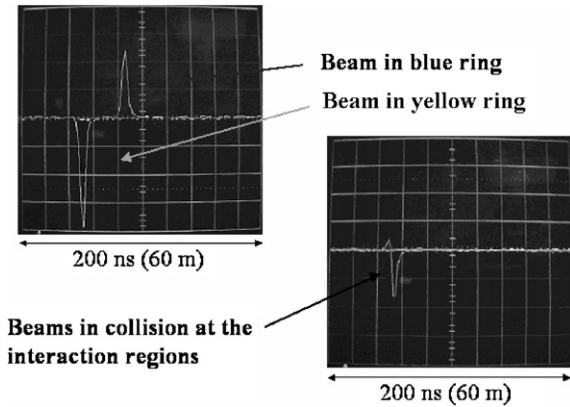


Fig. 11. Bringing beams in RHIC longitudinally into collisions.

the same betatron tune information at the second part of the ramp—from the transition crossing. One of the regular Schottky detectors on line scan is shown in Fig. 8.

2.3. Measurements of the beam profiles

The ionization profile monitors (IPMs) in RHIC detect electrons from the collisions of the gold ions with the residual gas. To avoid a spread of electron signals in a path towards the multi-channel plate detectors they are confined by a magnetic field of $B = 1$ T. One of the profiles is presented in Fig. 9.

2.4. Wall current monitor results

During the acceleration cycle the wall current monitors in both rings were recording the longitudinal profiles as presented in Fig. 10. A time of the transition crossing was defined very precisely by the wall current monitor signal as shown in the middle of the Fig. 10.

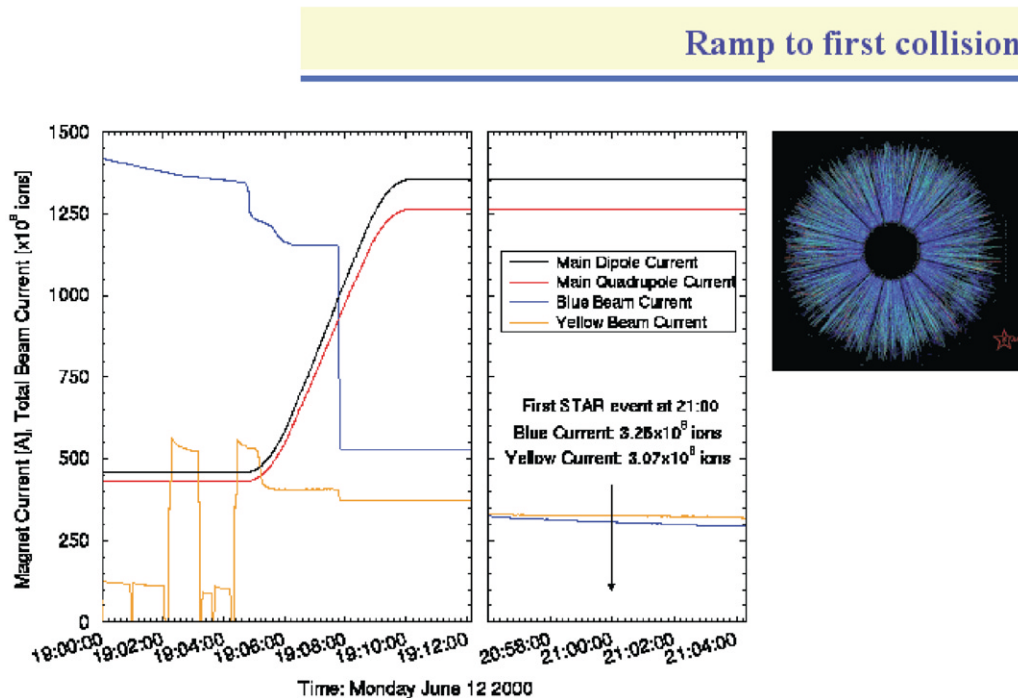


Fig. 12. First collisions recorded in RHIC in June 12, 2000.

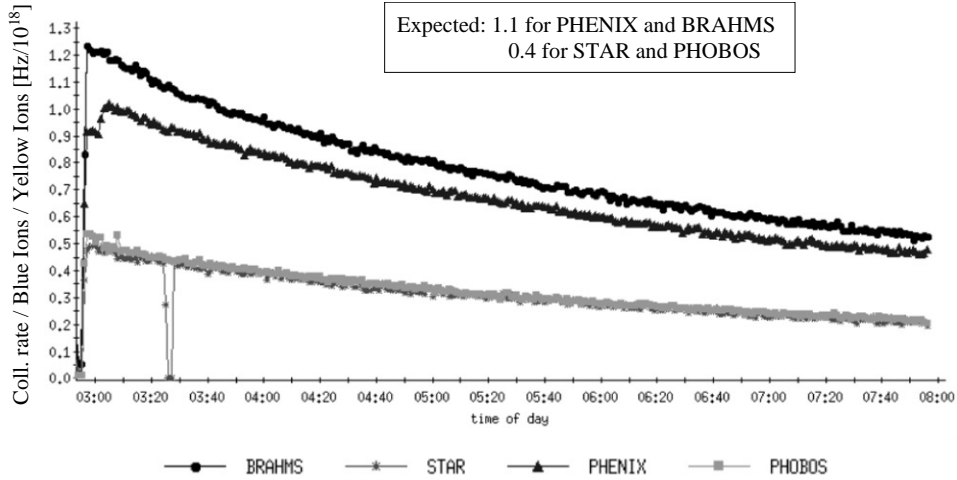


Fig. 13. Specific luminosity as a function of time during one RHIC fill of approximately 5 h. β^* in PHENIX and BRAHMS is 3 m and 8 m in STAR and PHOBOS, respectively.

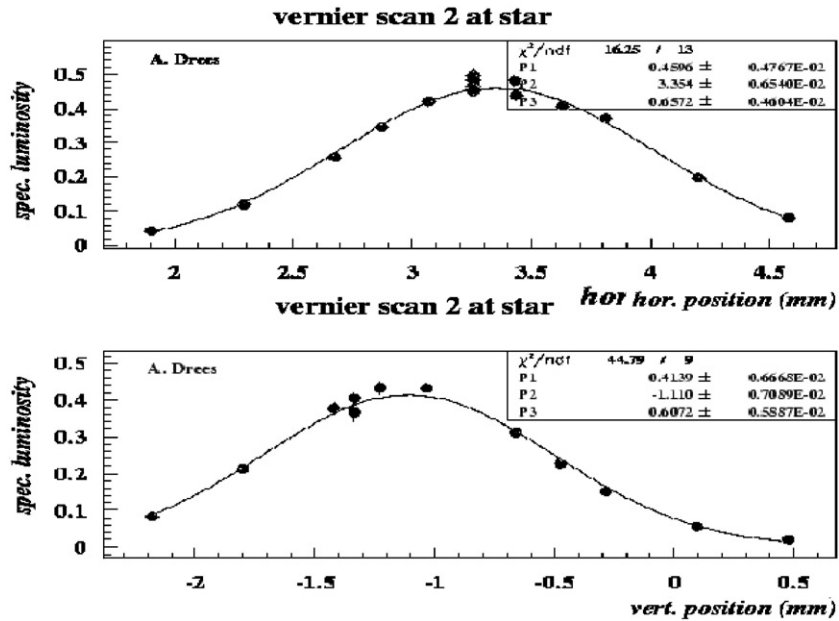


Fig. 14. Vernier Scans at STAR with Gaussian fits. Error bars are statistical only. P1 corresponds to the maximum specific luminosity, P2 to the peak position and P3 to the beam profile (σ) in mm.

3. Establishing collisions

At the end of the acceleration cycle two beams were first longitudinally brought by cogging into collisions with help of a specially dedicated RF wall current monitor, located at the interaction

point at 4 o'clock. This process of bringing two beams to cross at interaction points is shown in Fig. 11.

The second display of the Fig. 11 shows condition when bunches were colliding at each IP. This was always confirmed at the same time by

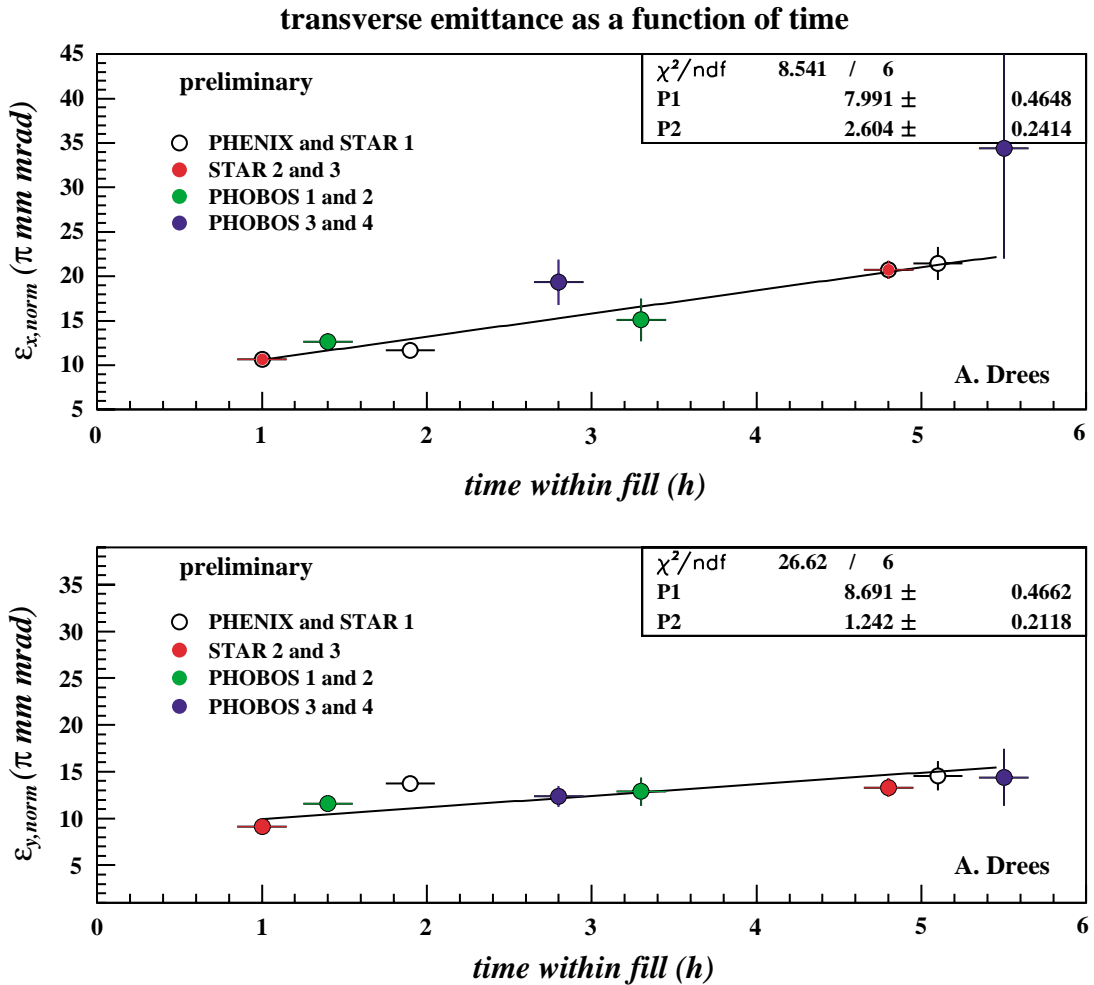


Fig. 15. Beam profiles measured during the stored beams by the Vernier scans.

enormous rise in the rates of the “Zero Degree calorimeters” at each of four experiments. The collision rate was measured using identical Zero Degree Calorimeters (ZDC) at all four interaction regions.

The first collisions were recorded on June 12, 2000 by the first STAR event shown in Fig. 12.

3.1. Zero Degree Calorimeters and Vernier Scans

Collision rates were determined using coincidence signals from both arms of the ZDC detectors at the experimental IRs. Using these

rates, which were displayed on-line in the Main Control Room, beams were steered through the various interaction regions. This way luminosity could not only be monitored and archived but could also be optimized at each individual IR. Due to the lack of reliable beam profile data an emittance value was assumed to determine the expected collision rates. Fig. 13 shows the specific luminosity as a function of time during a fill with $\sqrt{s} = 130$ GeV in August 2000. The expected rates correspond to the peak value at the beginning of the store based on a normalized emittance of 15π mm mrad.

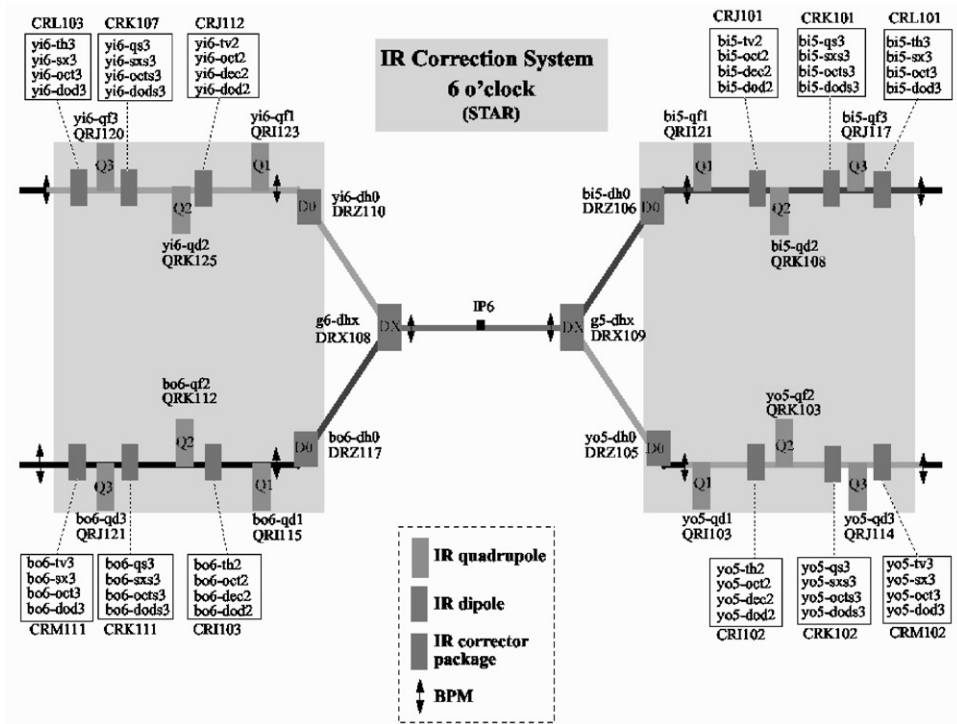


Fig. 16. The Triplet quadrupoles in RHIC with a special nonlinear corrector at one of the IR (STAR).

In addition to monitoring luminosity the ZDC detectors were used for beam studies by performing Van der Meer (or Vernier) Scans [4]. A scan is performed by setting the corrector magnets to sweep one beam stepwise across the other. The usual step size was set to 200 μm . The actual position is measured by beam position monitors located at the inner side of the DX magnets and extrapolated to the center of the IR. A total of 8 scans was done in both planes. Gaussian fits were applied to the collision rates as a function of the position of one beam with respect to the other. An example is shown in Fig. 14. The fit results yield the maximum luminosity, the beam profiles in both planes assuming the same beam sizes for both beams, and the peak position. A series of the Vernier scans allowed a study of the beam transverse growth in RHIC during the storage. This is important because the intra-beam scattering of the fully stripped gold ions is estimated to be a major reason for transverse and longitudinal beam growth. One of these results is presented in Fig. 15.

3.2. Interaction region quadrupoles nonlinearity measurements

The interaction region quadrupoles are expected to be the most important contributors to the nonlinearities at the top energy. There are especially designed correction elements placed between the triplet quadrupoles to make nonlinear corrections, as presented in Fig. 16.

This is due to a very large betatron function within them. Series of betatron tunes versus amplitude measurements were performed at injection. The betatron tunes were measured for each beam offset, intentionally introduced at the IR quadrupoles as presented in Fig. 17.

3.3. Collimation

Two copper plate beam collimators, one per RHIC ring, are located at the 8 o'clock straight section on both sides of the IP. After the collision mode was established, studies with the betatron

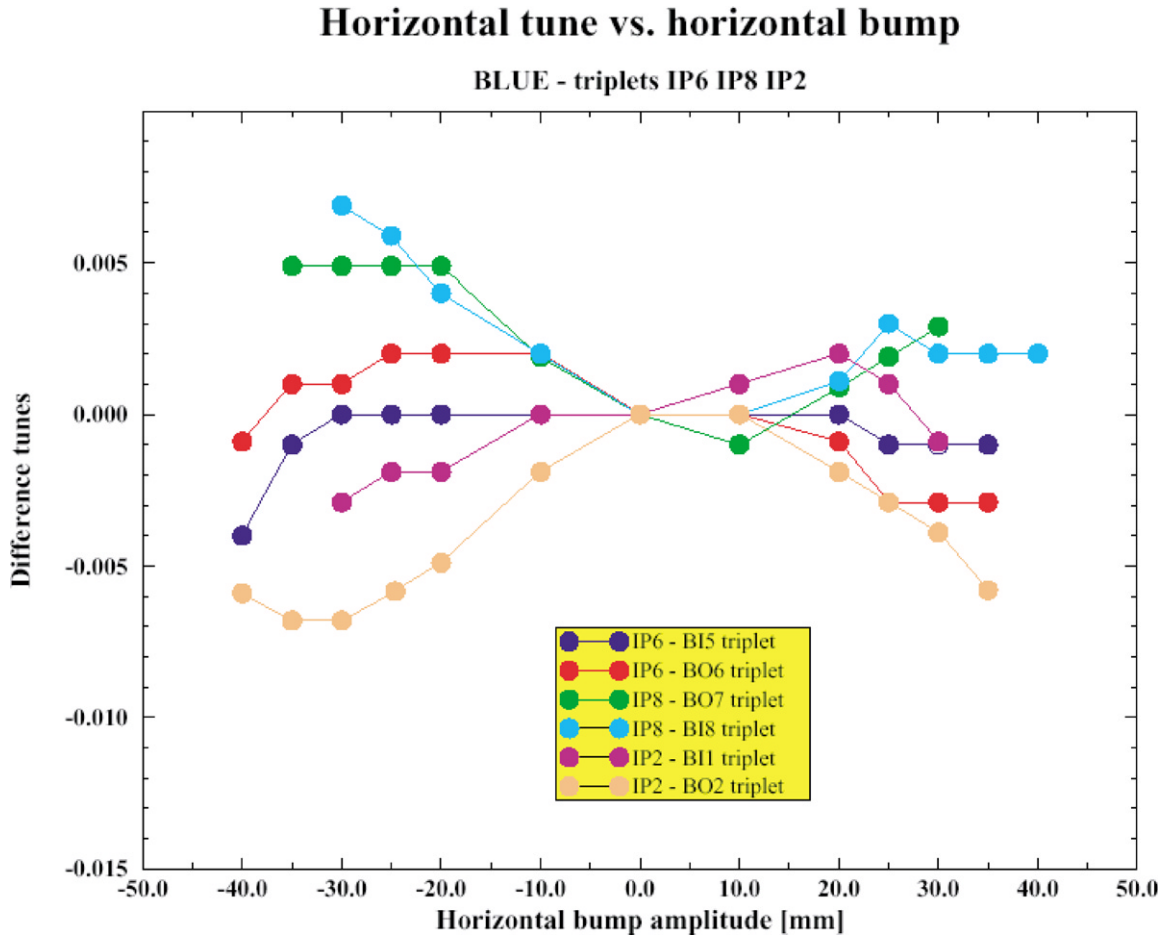


Fig. 17. Tune versus amplitude dependence measured at all six Interaction Region quadrupoles.

collimators were performed. The fast beam loss monitors—PIN diodes are located downstream of the collimators. With movement of the copper jaws towards the beam the signals from the fast beam loss monitors showed clearly that beam halo was removed. This behavior was reproduced every time the scrapers were moved towards the beam edge.

Additional studies of the beam diffusion and the beam size measurement were performed. Fig. 18 shows the counting rate from one PIN diode downstream of the scraper location as a function of time while the scraper was moved into and pulled out of the beam pipe.

4. Summary

RHIC RUN2000 commissioning and first operation was very successful. Full design luminosity with gold ions and collisions with polarized protons are planned for RUN2001. Other systems to be commissioned in the next run are: Phase Lock Tune Feedback, γ_t jump with all power supplies delivered, storage cavities will make short bunches, beta squeeze with all power supplies installed, and the bent crystal channeling collimation. The set-up with the bent single crystal is shown in Fig. 19.

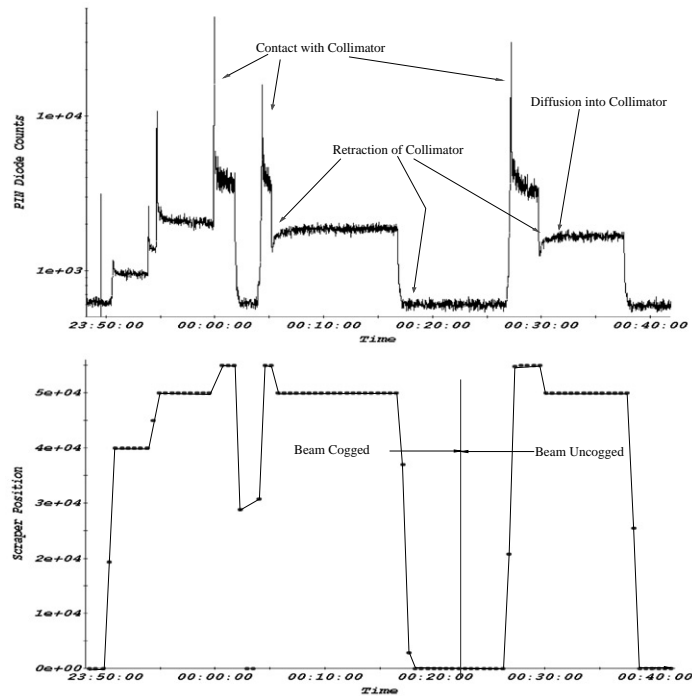


Fig. 18. PIN diode signal as a function of time (upper plot) and scraper position as a function of time (lower plot).

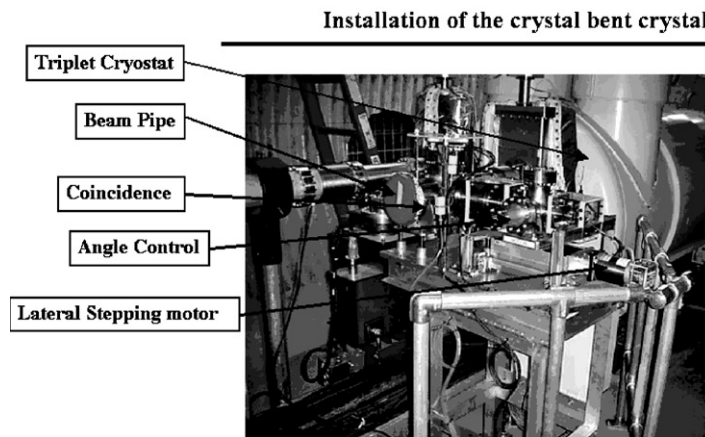


Fig. 19. The bent crystal channeling set-up being installed in RHIC.

References

- [1] D. Trbojevic, Commissioning of RHIC with Gold Ions, Invited talk Proceedings of the HEACC2001 The 18th International Conference On High Energy Accelerators, March 26–30, 2001, Tsukuba, Japan, March, 2001.
- [2] W. Fischer, A. Jain, S. Tepikian, Beam based Measurements of Persistent Current Decay, RHIC Notes: C-A/AP/32 (to be published in Phys. Rev. D), /newline (http://www.rhichome.bnl.gov/AP/ap_notes/cad_ap_index.html).
- [3] M. Blaskiewicz, J.M. Brennan, P. Cameron, A. Drees, J. Kewisch, T. Roser, K. Smith, C. Tang, Measuring α_1 in RHIC, BNL-CAD Note C-A/AP/19,07/2001, http://www.cadops.bnl.gov/AP/ap_notes/cad_ap_index.html.
- [4] S. van der Meer, ISR-PO/68-31, KEK68-64.